

VERTICAL LIFT PLANETARY AERIAL VEHICLES: THREE PLANETARY BODIES AND FOUR CONCEPTUAL DESIGN CASES

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Abstract

NASA Ames Research Center has been studying the feasibility of vertical lift aerial vehicles to support planetary science and exploration missions. Besides Earth, it appears that there are three planetary bodies within our solar system where vertical flight might not only be theoretically feasible, but would also have unique mission capabilities that no other platform (ground-based, aerial, or orbital) could provide. Several vertical lift vehicle configurations might be applicable for planetary science missions. This paper presents a few representative conceptual design cases and the design challenges inherent in their development. Finally, more detailed comments are directed to the issues inherent in developing a NASA 'Mars Scout' mission employing the use of a Martian autonomous rotorcraft.

Introduction

Humankind's understanding of the universe has undergone tremendous advances over the last few decades. Robotic missions to planetary bodies within the solar system have been particularly instrumental in achieving this understanding. But, planetary science is at a crossroads. A new generation of robotic explorers – with substantial improvements in autonomy, mobility, power/energy availability, and instrumentation sophistication - is required to make further advances. Successful development of a new generation of robotic explorers, including all of the attendant technologies for their operation, will also aid in the ultimate transition from robotic to human exploration of the solar system.

Recent research has focused on the feasibility of developing vertical lift aerial vehicles that could aid in the exploration of various planetary bodies in our solar system. Specifically, the utility of vertical lift aerial vehicles to support missions to Mars, Titan (a moon of Saturn), and Venus is being studied. Recent advances in autonomous system technology, microelectronics, ultra-lightweight structural materials, innovative power systems, and low-Reynolds number, compressible flow aerodynamics have been instrumental in

establishing the conceptual viability of vertical lift planetary aerial vehicles.

Table 1 summarizes a few of the important geophysical and atmospheric properties of Mars, Titan, and Venus. The corresponding properties for Earth are also provided as a reference.

Table 1–Planetary Description (Ref. 1)

	Mean Radius (km)	Gravity (m/s ²)	Mean Surface Atmos. Temp. (° K)	Mean Surface Atmos. Pressure (Pa)	Mean Surface Atmos. Density (kg/m ³)	Atmos. Gases
Earth	6371	9.82	288.2	101,300	1.23	N ₂ 78% O ₂ 21%
Mars	3390	3.71	214	636	1.55x10 ⁻²	CO ₂ 95% N ₂ 2.7% Ar 1.6% O ₂ 0.1%
Titan	2575	1.354	94	149,526	5.55	N ₂ 65-98% Ar<25% CH ₄ 2-10%
Venus	6052	8.87	735.3	9.21x10 ⁶	64.79	CO ₂ 96% N ₂ 3.5%

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Achieving vertical flight for Mars, Titan, and Venus will not be easy to accomplish. Nonetheless, preliminary work to date has been

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promising (Refs. 2-12). Development of such vehicles will be a tremendous engineering undertaking – both in terms of technical risk and scientific payoff.

Yet, despite the technical challenges for vertical lift planetary aerial vehicles, the most difficult hurdle for the development of these vehicles is likely to be both perceptual and programmatic in nature. Applying rotary-wing technologies to planetary science applications will require the development of cross-cutting technologies that must bridge the interests of a diverse group of research and technical communities -- “Strategic Enterprises” -- within NASA. It will be difficult, but not impossible, to bridge these disparate interests/requirements enabling the successful launch of vertical lift planetary aerial vehicles. Initiating such an engineering program would enable a wholly new technical discipline, leading to a truly “revolutionary” new approach to planetary science data gathering.

Four conceptual design cases will now be discussed that will illustrate the technical opportunities and design challenges of vertical lift planetary aerial vehicles. Finally, a notional NASA “Mars Scout” mission will be discussed in the context of a Martian autonomous rotorcraft performing aerial survey and sampling flights in conjunction with in-situ analysis science investigations back at a lander/primary-base.

Mars Coaxial Helicopter

Mars has been described as the most terrestrial of all the other planetary bodies in the solar system. And yet it is clear, from an aeromechanics perspective, that Martian rotorcraft will be very different from their terrestrial counterparts. Martian autonomous rotorcraft will have very large lifting-surfaces and will be required to have ultra-lightweight construction (Fig. 1). Further, Mars rotorcraft will have a unique combination of low Reynolds number and compressible flow aerodynamics, require new types of propulsion systems, and require high levels of vehicle autonomy. Some early work and discussion on Martian vertical lift vehicles can be found in Refs. 2-3 and 8-9.

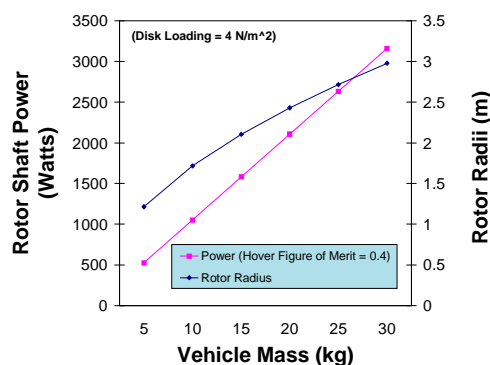


Fig. 1 – General Sizing Trend for an Isolated Mars Rotor

Recent work at NASA Ames has focused on a coaxial helicopter configuration for early Mars exploration missions (Fig. 2).

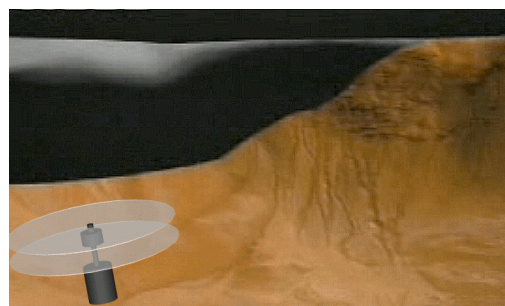


Fig. 2 -- A Coaxial Helicopter Configuration for Mars Exploration

Such a vertical lift aerial vehicle could aid in NASA’s “search for water” and “hunt for life” astrobiology objectives for Mars. A Mars coaxial helicopter would be more compact – and therefore more easily transportable from Earth – than other alternate rotorcraft configurations.

Fig. 3 shows first-order estimates of the forward-flight performance of a range of Mars coaxial helicopters sized from 10 to 50 kg. The performance estimates for these small coaxial helicopters assumes that the rotor tip Mach number is held constant at 0.65 and the disk loading is 4 N/m^2 . A very conservative induced power constant and mean blade profile drag coefficient was used for the rotor performance estimates in Fig. 3. Performance estimates for the coaxial helicopter configuration conform to the methodologies noted in Refs. 13-14. Similar aerodynamics and rotor performance characteristics are noted for rotary-wing micro air vehicles (Ref. 15). As can be readily seen, the rotor profile drag is a major contributor to the overall rotor power. There is almost a

negligible ‘power bucket’ for these vehicles. This performance estimate conservatism accounts for: 1. the high profile drag typical of very low Reynolds number airfoils; 2. the use of a bluff cross sectional shape for the inboard blade spar (out to 40% blade span); 3. the effect of large blade-root cutouts to allow for rotor blade fold and telescoping (for vehicle transport/deployment); 4. the high induced losses for low aspect ratio rotor blades with large blade root cutout. To achieve significant improvements in rotor profile power it will be necessary to use an improved low-drag inboard spar design (using a streamlined spar cross-section and reducing the blade root cutout) and improved low Reynolds number airfoils. The above rotor changes, though, will likely affect the volume of the stowed vehicle during transit to Mars. It is expected that substantial improvements in the rotor profile drag and vehicle parasite drag – as compared to the values used in these initial performance estimates - will be achieved as planned detailed computational and experimental investigations are made into Mars rotorcraft configurations.

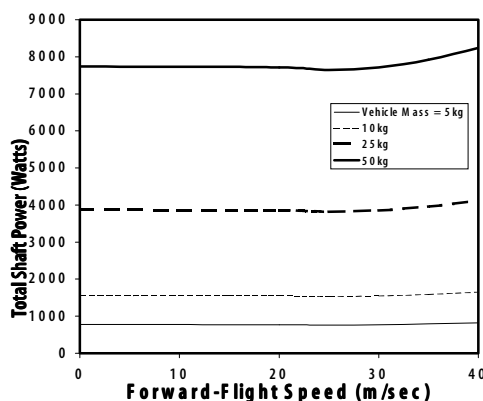


Fig. 3 – Mars Coaxial Helicopter Performance Estimates

Fig. 4 is an illustrative weight trend plot for the small, high-power density, electric motors potentially suitable for Mars rotorcraft configurations in the under 100kg weight class (Refs. 16-17). Given the singular nature of vertical lift planetary aerial vehicles, deriving weight estimates for key vehicle subsystems is a difficult but crucial design challenge. Weight trend methodologies (for example, Refs. 18-21) used in conventional rotorcraft preliminary design can only provide general insight at best.

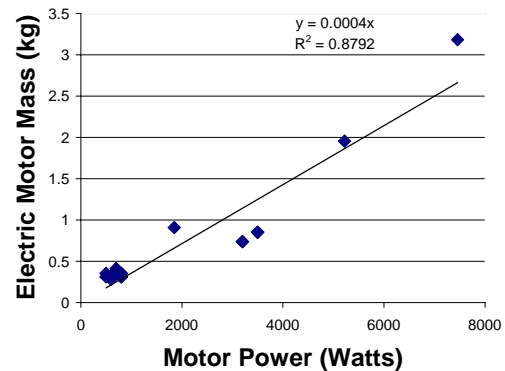


Fig. 4 – Illustrative (Current Technology) Small Electric Motor Weight Trend

Fig. 5 shows first-order estimates for vehicle range as a function of fuel/energy-source weight fraction for a 10 kg vehicle, at a forward flight speed of 40 m/s. Three families of curves are shown in the figure: range estimates using battery technology, estimates for fuel cells, and propulsion from a hydrazine-based Akkerman engine (Ref. 22). An Akkerman engine is a monopropellant-based propulsion system and, therefore, should operate satisfactorily in the carbon-dioxide-dominated atmosphere of Mars. It has been successfully used on high-altitude, long endurance terrestrial experimental aircraft.

Many factors must be accounted for in the propulsion system used for a Mars rotorcraft. Though hydrazine-based Akkerman engine technology promises the greatest range benefits for such vehicles, having a “clean” non-volatile (and non-toxic) energy source for such vehicles has much merit. Even among the various fuel-cell technology choices (non-regenerative versus regenerative systems and different types of reactants) each will have their relative advantages and disadvantages. Environmental contamination from fuel-cell by-products (from non-regenerative systems which expel/exhaust the fuel-cell products) can not be allowed to bias the science mission measurements being made. (For example, water vapor ‘exhaust’ from a hydrogen and oxygen non-regenerative fuel-cell could clearly contaminate the ‘search for water’ measurements/results.) Finally, though solar power may seem to promise a virtually inexhaustible energy source for a Mars rotorcraft (where its batteries or fuel-cells are recharged by a lander’s solar array panels), this is an overly optimistic viewpoint. In reality, the duration of a mission is just as likely to be determined by the amount of operational resources available on Earth as any other factor. Additionally, there are practical limits as to how long a solar array can deliver power efficiently on Mars due to dust adhesion/accumulation on

the solar array panels. Trade studies between hydrazine propulsion and fuel-cell systems for a Mars vertical lift aerial vehicle merit continued investigation.

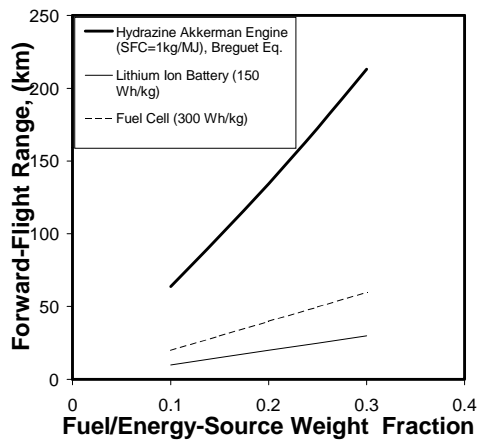
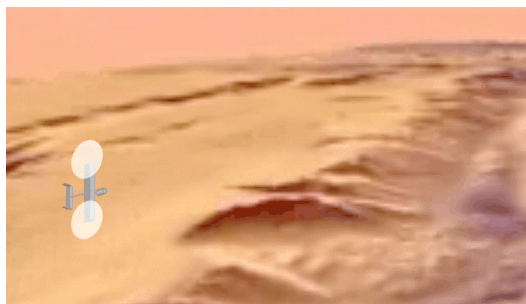


Fig. 5 – Mars Coaxial Helicopter Range Estimates

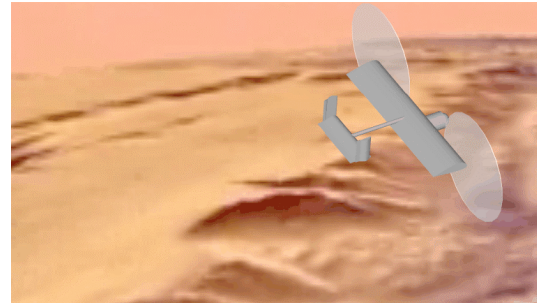
The flight dynamics of a Martian rotorcraft will be quite different compared to its terrestrial counterparts. The rotors for a Martian rotorcraft will have very low Lock numbers and will have very low aerodynamic damping. The rotor blades will also likely have relatively low values of torsion and bending stiffness because of their large blade planform area and ultra-lightweight structure. Yaw control for a Mars coaxial helicopter configuration will be maintained by differential rotor collective (resulting in differential torque) instead of relying on fixed tail surfaces as is done with most conventional terrestrial coaxial helicopters.

Mars Tiltrotor

A tiltrotor is a particularly attractive configuration (Fig. 6) for Mars exploration. A tiltrotor represents a good compromise between hover performance and cruise range/endurance.



(a)



(b)

Fig. 6 -- A Mars Tiltrotor: (a) helicopter-mode in vertical climb over Valles Marineris; (b) airplane-mode

Fig. 7 presents some initial sizing estimates for a small (10 kg) autonomous Mars tiltrotor configuration. Fig. 7 shows the trend of rotor size as a function of rotor mean lift coefficient and tip Mach number. A notional rotor design point of $M_{tip}=0.7$ and $C_L=0.4$ is noted on the figure. As expected the resulting proprotors are quite large. One of the biggest issues for the Mars tiltrotor configuration is that the deployment of a tiltrotor on the surface of Mars will be fairly complicated, and will require astronaut-assisted assembly or some type of autonomous assembly process on the lander platform.

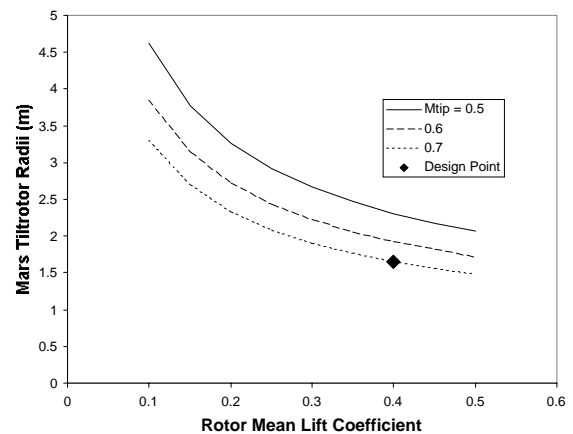


Fig. 7 – Mars Tiltrotor Rotor Size Estimates (Total Vehicle Mass = 10 kg)

Fig. 8 shows wing planform area as a function of maximum wing lift coefficient and the end-of-conversion Mach number (airspeed at which the wing, versus the rotors, carries all the vehicle lift). Three considerations constrain the wing sizing effort: first, there is a maximum advance ratio to which the rotors can fly edgewise in helicopter-mode (because of high vibratory loads); second, maximum wing lift coefficient is significantly lower for the low

Reynolds number regime typical of flight in the Martian atmosphere; third, there is a minimum wing stiffness required for aeroelastic stability (particularly for ultra-lightweight structures). It is beyond the scope of this paper to address these design considerations in other than a qualitative sense.

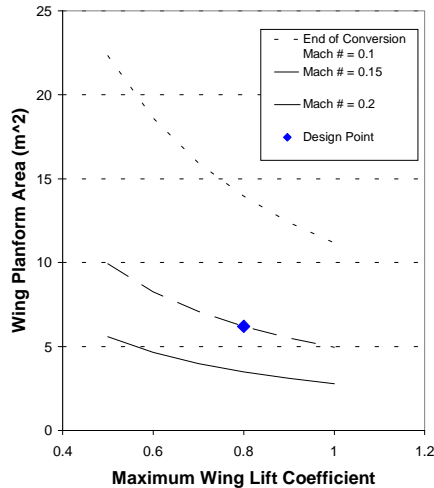


Fig. 8 – Mars Tiltrotor Wing Area Size Estimates (Vehicle Mass = 10 kg)

Fig. 9 shows preliminary range estimates (using the Breguet range equation) of the 10 kg Mars tiltrotor configuration, assuming propulsion is provided by an Akkerman hydrazine piston engine, for various vehicle L/Ds and fuel fractions. The specific fuel consumption (SFC) constant used for the Akkerman hydrazine piston engine is 1.0 kg/MJ (Ref. 22). A typical value for conventional terrestrial tiltrotor aircraft is $L/D \sim 7$.

As shown in Fig. 9, a Mars tiltrotor using hydrazine piston engine propulsion will be a medium-range planetary aerial vehicle. In order to improve vehicle range, in addition to improving L/D efficiency of the aircraft, the propulsion system SFC must be improved. This will necessitate developing alternate propulsion systems having improved SFC – perhaps those involving propellants generated by in-situ production techniques.

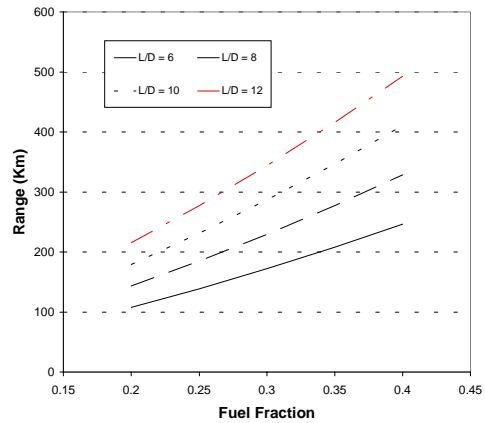


Fig. 9 – Breguet Range Estimates for a Mars Tiltrotor

Besides potentially having range and endurance advantages over other Mars rotorcraft configurations, Mars tiltrotors will also likely be able to operate at higher altitudes (~1km above ground level). Many geologically interesting sites on Mars may only be accessible with a Mars tiltrotor versus a helicopter configuration.

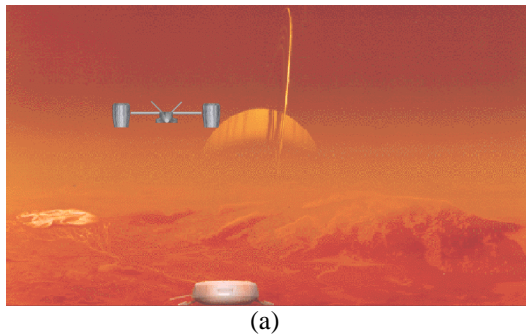
Deserving considerable follow-on analysis is aeroelastic/whirl-flutter stability for tiltrotor vehicles constructed of ultra-lightweight and low stiffness structures. A considerable amount of creativity may well be required to insure satisfactory cruise speeds with acceptable stability margins for such radically different vehicles and structures compared to their terrestrial counterparts.

More discussion related to Mars rotorcraft, with respect to the NASA Mars Scout program, can be found in the Appendix.

Titan Tilt-Nacelle VTOL

Several types of rotorcraft, or alternatively powered lift vehicles, could be developed for aerial exploration of Titan (Refs. 4-6, 7, 12). Such vehicles will likely have electric propulsion driving their rotors or fans. In particular, ducted fan configurations such as tilt-nacelle aircraft are perhaps well suited for Titan (Fig. 10). Use of electric propulsion in conjunction with a lander-based power source will maximize the number of flights (and, therefore, remote sites that can be visited and samples and measurements made). Ducted fan aerial vehicles would inherently be more robust during take-off or landing in an unknown,

potentially hazardous, environment as compared to conventional rotors.



(a)



(b)

Fig. 10 -- A Titan Tilt-Nacelle VTOL: (a) take-off; (b) cruise.

Fig. 11 shows a first-order estimate of hover total shaft power for a notional Titan tilt-nacelle VTOL vehicle having two ducted fans that can pivot at the wing tips (similar in configuration to the Doak VZ-4). A conservative shroud thrust fraction of 0.3 (i.e., 30% of the total thrust is provided by the duct/nacelle aerodynamics in hover) is used in the hover performance estimate. The hover performance and fan sizing estimates are for a disk loading of 600 N/m^2 , a fan blade tip Mach number of 0.7, and a fan blade solidity of 0.25. A Titan VTOL's ducted fans will be very small and consume very little power as a result of the high atmospheric density and low gravity field for Titan.

Initial mission concepts being studied at NASA Ames would employ a lander-based architecture where small ducted fan tilt-nacelle vertical take-off and landing (VTOL) aircraft could use the lander as a primary base site. The lander would service and support (including battery/fuel-cell recharging) the vertical lift aerial vehicles. This lander/aerial vehicle power source will inevitably be nuclear in nature (Radioisotope Thermoelectric Generators (RTGs) or Stirling cycle reactors); because of the great distance of Titan from the sun, and its atmospheric haze, solar power is not an acceptable alternate power source. RTG units -- in the under 250 Watt class -- are a proven technology. This size of RTG units have been demonstrated in previous outer planetary missions.

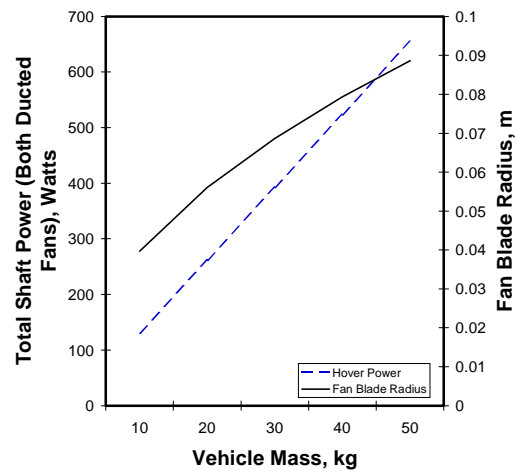


Fig. 11 -- Ducted Fan Hover Performance for Titan Vehicle

Fig. 12 shows range estimates for a 50 kg Titan twin tilt-nacelle/ducted-fan VTOL vehicle, assuming power matching between the hover and cruise design points. The range estimates are based on the estimated power from Fig. 11, with reasonable drive train and electric motor efficiencies applied. The cruise speed is assumed to be 50 m/s. These range estimates assume minimum hover/loiter time. The Titan VTOL cruise speed is relatively low to reflect the higher atmospheric density of Titan.

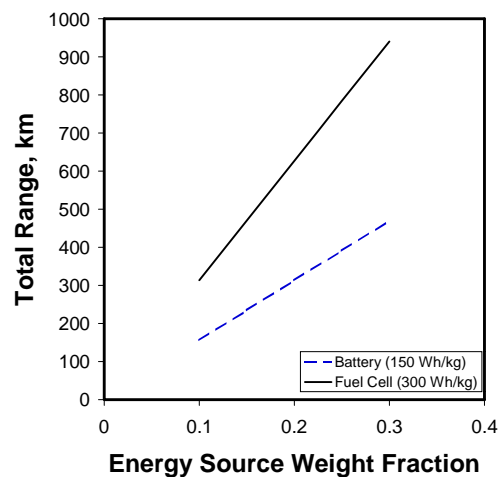


Fig. 12 -- Range Estimates for a Twin Ducted Fan Titan VTOL

By 2004, the joint NASA, ESA, and Italian space agency Cassini space mission will reach Saturn's orbit and release the Huygens probe (descending via parachute) into Titan's atmosphere. The Huygens atmospheric probe and the complementary Cassini observations will provide invaluable insights into the atmospheric chemistry/properties of Titan.

Fundamental insights into pre-biotic organic chemistry may result from the exploration of Titan. With the anticipated success of the Cassini/Huygens mission there may be an opportunity to take advantage of the excitement underlying this adventure to advocate possible follow-on missions – including those employing Titan VTOL vehicles.

Venus Hybrid Airship

Of the three planetary bodies besides Earth where it theoretically is feasible to design and fly vertical lift aerial vehicles, Venus will likely pose the greatest challenge. The extremely high atmospheric densities near that planet's surface (plus the near-Earth-magnitude of its gravitational field) would suggest that a buoyant, or semi-buoyant, vehicle might represent the most practical design for exploration of Venus (Fig. 13). The airframe of a Venusian hybrid-airship would be a rigid hull, capable of sustaining substantial pressure differentials across (interior/exterior) the hull surface.

Venus' high surface temperatures also pose tremendous challenges for aerial vehicle design. Though active and passive technologies exist for thermal management of planetary science hardware, extended operation of such hardware near Venus' surface is currently problematic with today's technology. This will mean, for example, that 'waste heat' will have to be minimized by keeping the power required for flight to an absolute minimum (thus necessitating buoyancy fractions greater than 75%).

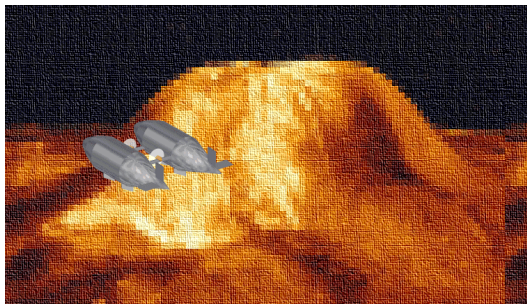


Fig. 13 -- A Notional Venusian Hybrid Airship with Twin Hulls and Tandem Tilting Propellers

Fig. 14 shows first-order estimates of a notional Venus hybrid-airship's hull size. The results shown in this figure assume a hybrid-airship buoyancy fraction of 0.9 and a propulsion energy-source (batteries, fuel cells, etc.) weight

fraction of 25%. Helium is assumed as the hybrid-airship lifting gas. A thin skin of titanium alloy is assumed for the hull. Hull skin thickness using titanium alloys ranges from 0.5 to 1 mm thick for vehicle mass from 10 to 50 kg. A similar analysis for low-altitude balloons for exploration of Venus' atmosphere has been previously proposed (Ref. 23).

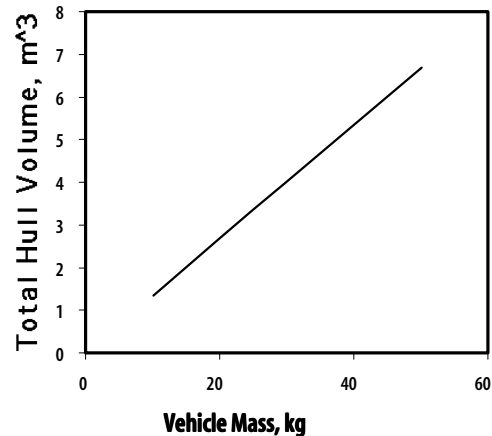


Fig. 14 – Hull(s) Size Estimate

Fig. 15 shows a first-order estimate of the hover performance and sizing of a tandem propeller combination (sandwiched between twin airship hulls) that could be used to take-off and land from Venus' surface. The performance and sizing estimates shown in the figure assume the airship buoyancy fraction of 0.9 (therefore, the two propellers have to lift only 10% of vehicle weight in hover), a tip Mach number of 0.1, a 200 N/m² disk loading, and a solidity of 0.4 for the propellers.

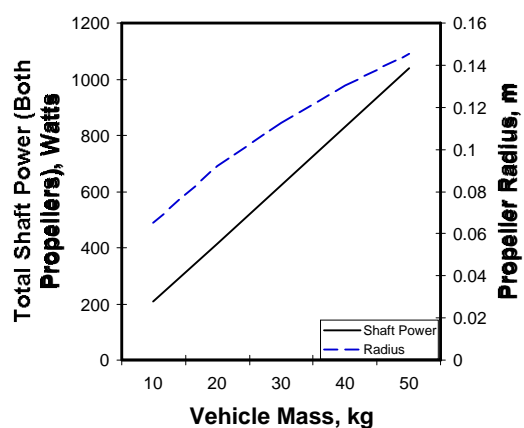


Fig 15 – Hybrid-Airship Propeller Hover Performance and Sizing Estimates

In the near-term, aeromechanics work on aerial vehicles for exploration of Venus might benefit from collaborative work with naval researchers investigating undersea submersible robots.

Planetary science missions to Venus, though perhaps not as frequent or of as great public interest as Mars and outer planet missions, nonetheless will ultimately test the capabilities of vertical lift planetary aerial vehicles to gain a true sense of Earth's "sister" planet.

Concluding Remarks

Over five hundred years ago, Leonardo Da Vinci envisioned flight by means of a vertical lift aerial vehicle. This progenitor of the helicopter inspired generations, including the early pioneers of the rotorcraft industry and research community. Over the last six decades the helicopter has found, among other applications, great utility in aiding in terrestrial exploration. Preliminary design studies by both NASA and U.S. universities have established the theoretical feasibility of vertical flight in extraterrestrial atmospheres. Much work remains. Nonetheless, with the new twenty-first century, there lies the opportunity to inspire the whole of humankind with the full potential of rotorcraft, by demonstrating vertical flight on other planetary bodies in our solar system.

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Appendix -- Rotorcraft and the NASA 'Mars Scout' Program

The most likely near-term candidate for a vertical lift planetary aerial vehicle will be for the exploration of Mars. The National Aeronautics and Space Administration's most recent revised Mars exploration plan includes

the development of Mars Scout missions. Mars Scout missions are intended to be competitively selected projects that complement the baseline Mars program established within NASA. An initial solicitation has been circulated for Mars Scout concept studies (Ref. 24). A formal Announcement of Opportunity is expected by first-quarter calendar year 2002. Both the baseline Mars Exploration Program and the Mars Scout missions are directed to meet the goals and objectives detailed by the planetary science community's Mars Exploration Program/Payload Analysis Group (MEPAG). A key feature of many of the MEPAG objectives is the requirement for multiple and diverse site investigations and sampling missions. A Mars rotorcraft/scout would represent a satisfactory solution for this requirement (Fig. 16).

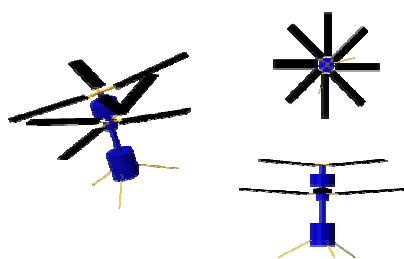


Fig. 16 – A Rotary-Wing Mars Scout

Many of the most interesting geological features on Mars lie in terrains that are essentially unreachable by wheeled vehicles and current landing systems. Examples include the headwaters of the newly discovered small Martian gullies and the layered cliff faces along the walls of Valles Marineris. Yet *in situ* exploration of these features is critical to understanding their formation and the role of water in Mars' present and past climate. A vertical lift planetary aerial vehicle (a Mars rotorcraft) would have the flexibility to takeoff nearby, transit to, then hover over and examine such high priority science targets. Unlike "single shot" fixed wing aircraft concepts, a Mars rotorcraft scout offers the opportunity to perform multiple flights by recharging at the lander.

A notional Mars Scout mission would entail landing on the Martian surface a suite of science instruments to study the geology and organic chemistry of Martian stratigraphic outcrops, rock fragments, soil and dust and determine its past water history and biological potential. The lander would likely be a variant of the 2003 Mars Exploration Rover (MER) lander and would carry a rotorcraft to image and obtain spectral data for geological sites, and to acquire

samples from up to 10 km or so distance from the lander.

The feasibility of vertical flight in the Martian atmosphere has been established by design studies by NASA Ames Research Center and independent analyses performed by several university teams (Refs. 25-29). Work on the Mars rotorcraft concept is transitioning from preliminary system analysis to proof-of-concept test article design, fabrication, and assessment and fundamental experimental investigations of the unique aerodynamics of these vehicles. In particular, an isolated rotor configuration -- designed to constraints compatible with flight in the Martian atmosphere -- has been designed and fabricated and is currently undergoing pre-test preparation for hover testing in a NASA Ames environmental chamber. Complementary work is also under way examining autonomous system technology and other critical enabling technologies for vertical lift planetary aerial vehicles.

The ultra-lightweight rotorcraft will operate largely autonomously and will be targeted to sites of interest identified from available orbital imaging and spectral data after the actual landing site is accurately determined. The rotorcraft will acquire high-resolution imaging and spectral data and return small samples of soil and rock fragments from the designated sites. The instrumentation carried by the lander will include an optical microscope, an Infrared (IR) spectrometer and a Gas Chromatograph Mass Spectrometer (GCMS).

The notional Mars Scout mission would capitalize on lander designs and science instrumentation that have already been developed and will, in addition, introduce new capabilities in addressing NASA's "follow the water" theme.

Science Goals and Objectives

Determining the mineralogy of the Martian surface material is the first step in understanding Martian geochemistry. *In situ* analyses of the Martian surface material can provide information on the mineralogy and volatile content of Martian surface material needed to characterize their geochemical and petrologic nature. Knowing the mineralogy of a sample of the Martian surface material provides data on the environment under which it was formed. This information can be used to better define the early environment of Mars especially with respect to the history of water. For example, clays and evaporitic salts require the presence of water for their formation; as a consequence, if they form part of the Martian surface material

their presence would be evidence for water to have been on the Martian surface for some length of time. Acquisition of multiple samples from a number of distributed sites is a key element of a Mars rotorcraft mission and will clearly enhance the understanding of the geochemical evolution of Mars.

A Mars Scout rotorcraft could follow a specific flight plan over interesting terrain, for example the course of a small gully or along a specific cliff face selected from orbital images. Forward and aft mounted cameras would provide target specific views unobtainable by fixed-wing aircraft or rovers. The rotorcraft will have the capability to land at remote sites. Landing-leg mounted instruments could include a microscopic imager for measurement of grain characteristics and sizes. If adequate payload weight margins could be achieved for the Mars rotorcraft, a sample-collecting scoop could be integrated into one landing leg to collect soil samples at the remote site that can be transported back to the lander for further analysis. Sites well suited to rotorcraft exploration include:

- Valles Marineris
- Young gullies
- Headwaters of outflow channels and valley networks
- Basal scarp surrounding Apollinaris Patera to search for hydrothermal spring deposits and explore sapping valleys.

Mission Description:

- Prime Mission: 10-15 Sols (a Sol is one Martian 'day') devoted to acquisition, and in-situ analysis, of soil and small rock samples immediately adjacent to the lander (using a robotic arm); 5-10 Sols for the set-up and checkout of a vertical lift aerial vehicle (an ultra-lightweight robotic Mars rotorcraft/helicopter) with the robotic arm; 1 sol to execute a short flight/hop and return of approximately a hundred meters or so (within line of sight of lander) to perform demonstration flight and initial sample return run; 20-30 Sols to perform a low altitude high-resolution aerial survey, of a radius of several kilometers with respect to the lander using the vertical lift aerial vehicle. All power to be provided by the lander solar array panels. Aerial vehicle to be recharged between flights by the solar array panels (4-6 Sols between aerial survey flights and 6-10 Sols for time between sample return flights).
- Secondary Mission: 20-40 Sols devoted to remote-site soil/rock sampling mission flights at a distance of several kilometers from the lander (over potentially hazardous terrain) via the vertical lift aerial vehicle (most of this

mission time will be dedicated to recharging or refueling the vehicle and in-situ analysis of the samples and communication of results to Earth). Note overall mission time will be affected by which of the two primary propulsion systems options are chosen for the vertical lift aerial vehicle.

Science Payload

Lander Instruments:

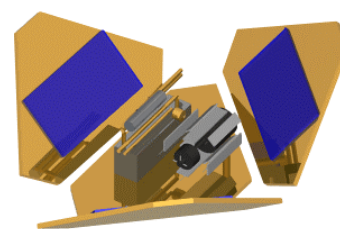
Microscopic imager
 IR Spectrometer or Raman Spectrometer
 Gas Chromatograph Mass Spectrometer (GCMS)
 Wide-field optical camera for documenting/tracking Mars rotorcraft take-off and landing; used also to guide lander robotic arm positioning for soil/rock sample transfer from the rotorcraft to the lander and to aid in the aerial vehicle set-up and recharging.

Vertical Lift Aerial Vehicle Instruments

Forward- and aft-mounted optical cameras for Guidance/Navigation and aerial survey images
 Sun tracker
 Atmospheric temperature and pressure sensors for flight readiness and documenting remote-site climatology
 Landing-leg-mounted camera for soil/rock sample identification and leg-integrated sample probe/scoop positioning
 Several vehicle health and flight safety, navigation and control transducers
 IMU and assorted accelerometers for flight control.

General Lander and Associated Equipment Description (Fig. 17a-e)

A lander carrier with solar array petals similar in configuration of the 2003 MER and Mars Pathfinder landers (Refs. 30-31); an in-situ instrument science module for processing and analyzing soil and small rock samples; a robotic arm for sampling/transferring rock samples and further, assisting set-up, handling, and usage of the Mars rotorcraft; the vertical lift aerial vehicle itself, with a transport frame and auxiliary support equipment; lander mission computer and communication package.



(a)

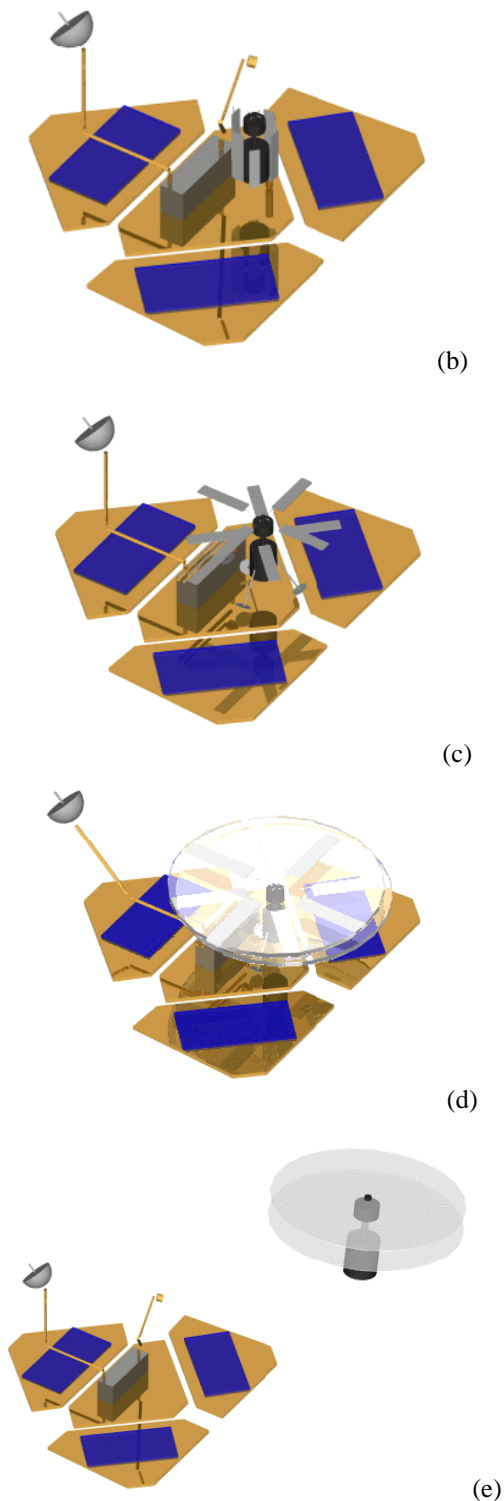


Fig. 17a-e – Mars Rotorcraft Deployment

Primary Objectives

- Examine mineralogical and biochemical characteristics of soil and small rock samples in support of scientific investigations for 'Hunt for Water,' 'Search for Life,' and the geological evolution of the Martian surface.
- Perform low-altitude, high-resolution aerial surveys of geologically interesting Martian surface features in hazardous or otherwise

inaccessible terrain for rovers and landers; identify remote-sites for follow-on sampling mission flights

- Perform a technology/flight demonstration of an autonomous vertical lift planetary aerial vehicle to support infrastructure development of a class of 'astronaut agents' that could enhance safety and mobility (and, thereby, mission science return) for human exploration of Mars.

Secondary Objectives

- Robotic Mars rotorcraft, after initial flight demonstration and aerial surveys would hover and land at geologically-interesting remote sites and use a sampling probe – such as a scoop – and pick-up small soil and rock samples; digital cameras and image processing software on the flight/mission computer would autonomously the most interesting samples to acquire. Recorded images will define the context (in relation to the surface characteristics in the vicinity of the sample and the morphology of the surrounding area) of the acquired samples. Samples would be returned to lander and placed in the in-situ sample analysis hopper; the Mars rotorcraft would be hooked up (with the lander robotic arm) to lander auxiliary systems for recharging.
- Aerial vehicle 'Final Flight' would be a one-way mission to maximize flight range distance from the lander primary-site. The Mars rotorcraft would carry a small science payload in place of the sampling probe to the maximum range remote-site. The science payload would focus on climatology experiments to complement primary-site measurements.

Science Implementation

Crucial to the success of any Mars Scout/Rotorcraft mission will be the formation of a strong project team that provides the critical multi-disciplined expertise and technology. Research and technical communities that heretofore have not interacted with each other will have to form close, efficient working partnerships. This process of opening communication and team building has begun between planetary scientists, spacecraft designers and mission developers, and the rotorcraft research community. But the magnitude of this task should not be underestimated; the cost of planetary exploration, coupled with the negative impact of mission failure, is such that a long process of confidence-building between these disparate communities will be required.

Mission and Flight System Architecture

The development of any type of planetary aerial vehicle will be a technically challenging enterprise, a vertical lift vehicle perhaps even more so. Not only are there significant technical issues to be overcome, but there are perceptual issues as well. Even in space it seems that the friendly rivalry of the fixed-wing versus the rotary-wing aircraft communities continues to thrive. But, even worse, compounding this competitive jostling for attention and potential adoption in the Mars exploration program are the rover and balloon/aerostat (and the 'hopper' and multiple small lander) proponents.

To minimize overall real and perceived risk, any Mars Scout rotorcraft mission will have to attempt to balance the risk of unproven aerial vehicle technology by maximizing the use of 'heritage' technology previously demonstrated with flight hardware. Therefore, a Mars Scout rotorcraft mission will likely model itself in many ways after the Mars Pathfinder and the 2003 Mars Exploration Rover (MER) missions.

A baseline Mars rotorcraft mass target should be assumed to be approximately 20 kg. At least one-half hour of flight should be sustained, with hover and take-off and landing from the lander and a remote site location. The ability to recharge/refuel back at the lander will be an essential mission feature. Two different propulsion strategies should be examined in parallel – for risk mitigation -- in the conceptual and preliminary design stages of a Mars Scout/Rotorcraft effort (fuel-cell versus Akkerman hydrazine engine). Further, because mass is always a critical issue in spacecraft design, tradeoff studies should be made for the aerial vehicle – varying the vehicle mass from 10 to 20 kg -- to examine the impact on mission performance versus risk. Finally, design studies and experimental investigations should continue throughout the early stages to benchmark coaxial helicopter configurations against quad-rotor vehicle designs. Both vehicle configurations have considerable merit/potential for early robotic missions to Mars (Refs. 26-28). By pursuing parallel investigation of both aerial vehicle types in the early stages of a Mars Scout development effort, a strong final mission candidate design will likely emerge.

Table 2 is a preliminary 'Science to Mission Traceability Matrix' for this notional Mars Scout rotorcraft mission. Information contained in this table is used by science team peers and reviewers, and mission planners, to assess whether or not a mission candidate concept can meet its identified goals and objectives.

Requirements on Notional Mission:

Orbiter	Not required; will utilize pre-existing communication assets and/or lander-based direct communication with Earth
Launch Vehicle	Delta II 7925-9.5
Launch Date	~ June 2007
Mission duration	90 Sols (upon landing)
Flight System Elements	Cruise stage; Entry, Descent, Landing system (EDL): Pathfinder/MER-style tetrahedron with inflatable airbags

Requirements on Spacecraft Flight System:

Control method	Spin stabilized; 2 rpm cruise stage.
Instrument Power	Minimum instrumentation (and power requirements) for trajectory corrections and spacecraft health monitoring; no spacecraft science instrumentation.
Special protection:	Mars rotorcraft will be composed of materials and sub-systems that need to be assessed for their environmental compatibility with spacecraft cruise stage.
Radiation environment	No RTGs required; solar and battery power only.
EDL Maneuvering:	None required beyond matching MER or Pathfinder Error Ellipses.

Requirements on Communications & Data System:

Data Volume (Mbytes per day):	~100 Megabytes (per flight)
Number of data downlinks per day:	1
Real time requirements:	None

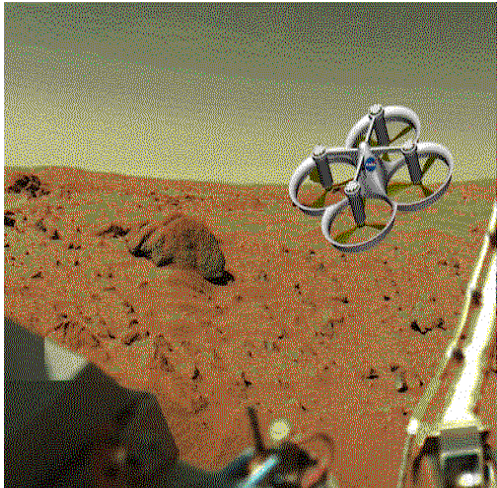
Table 2 - *Science-To-Mission Traceability Matrix*

Science Driver	Instrument Requirement	Mission Requirement	Flight System Requirement	Comm. and Ground Data System Requirement	Mission Operations Requirement	Technology Requirement
1. MEPAG Goal I, Objective A, "Determine if Life Exists Today," Investigation 2, 3.,5, 6	GCMS (Gas Chromatograph Mass Spectrometer) Microscopic Imager	1. Perform low-altitude, low-speed aerial survey and select remote-sites where geologic formations would suggest water was once existent; 2. Acquire at multiple sites soil and small samples to assess existence of clays, hemotites, and/or sedimentary rocks through spectrometry; 3. Through use of GCMS, assess potential of soil sample for containing organic compounds and/or levels of oxidants	EDL must be capable of delivering to the Martian surface a 20kg aerial vehicle; 20 kg of science analysis package/station; and a tetrahedral solar array 'petals' for power; a robotic arm and support frame for set-up and recharging	1. Aerial survey digital images will comprise the largest fraction (~75%) of data transmittal to Earth; aerial and remote-site (near- and far-field) images will need to be transmitted throughout mission duration in order to provide the scientific community the contextual background to accompany the soil and rock sample analyses; 2. Sophisticated software for science analysis, data prioritization and communication, and mission planning will be required for both the lander science station and the aerial vehicle.	1. Single shift required for Earth/Lander communication; 2. Two-three 'off-days' between complete data set downlink and initiation of next aerial vehicle flight required for science team preliminary analysis and planning;	A. Heritage Instrumentation B. Development of a 'Mars Rotorcraft' C. Develop In-Situ Handling & Processing Tools for the Lander Science Package/Station. D. From an overall Mars program risk management perspective, it would probably be best to couple a 'low risk' and a 'high risk' (such as one employing a Mars rotorcraft) during the same Mars transit window opportunity.
2. Goal I, Obj. B, "Determine if Life Existed in the Past," Investig. 1 & 2	IR (Infra-Red) Spectrometer Microscopic Imager	Through use of microscopic imager and rock preparation/processing tools (grinding/slicing) assess rock samples for paleobiology potential.	Sample handling and processing techniques need to be developed to transfer samples from rotorcraft to lander science module.	---	---	A. Microscopic imager and IR Spectrometer will be heritage from 2003 MER missions. B. Robotic arm will have partial heritage from Mars Polar Lander hardware
3. Goal I, Obj. C, "Assess Pre-Biotic Organic Chemistry," Investig. 1	GCMS	---	Cross-contamination between samples must be minimized. Proper cataloging, archiving, and/or disposition of samples must be provided for.	Sophisticated data management tools will be required to optimize 'data fusion' between the in-situ analysis results for soil and rock samples and the sample 'context' information derived from the aerial survey and remote-site imagery.	--	GCMS will have heritage dating back to the Viking lander missions.
4. Goal III, Obj. A, "Determine Present State, Distribution, and Cycling of Water," Investig. 2	GCMS Microscopic Imager APXS (Alpha Proton X-Ray Spectrometer)	Through use of the APXS assess the morphology of small rock samples for origin (volcanic versus sedimentary)	---	---	--	APXS will have heritage technology dating from the Mars Pathfinder mission.

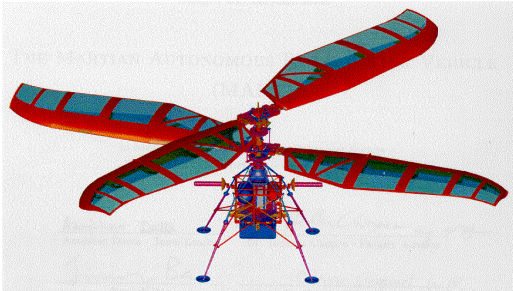
New Technology, Infrastructure and Risk Assessment

Heritage systems and technology will be used as much as possible in this notional Mars Scout mission, and will include as a minimum: all lander-based science instrumentation, the lander and aeroshell/entry vehicle configurations, and the spacecraft system. New technology for this notional Mars Scout mission will primarily be in the form of the Mars rotorcraft.

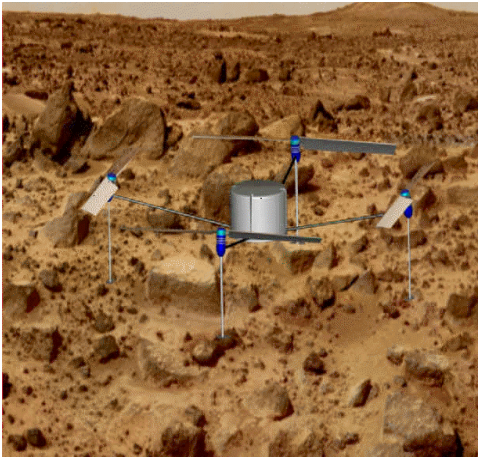
The current NASA Technology Readiness Level (TRL) for a Mars rotorcraft vehicle, as a whole, is TRL=2. Analytical assessments have been made of the Mars rotorcraft concept over the past two years both within NASA and other institutions (Refs. 2, 7, 11, 26-29).



(a)



(b)



(c)

Fig. 18 – University-Proposed Mars Rotorcraft Concepts; (a) Stanford Mars Mesicopter; (b) University of Maryland MARV; (c) Georgia Institute of Technology GTMARS

Through the co-sponsorship of Sikorsky Aircraft and NASA Ames, the American Helicopter Society, International conducted its Year 2000 university student design competition on Mars rotorcraft. These highly detailed design studies of the Mars rotorcraft concept – based on a common set of design requirements very much consistent with the notional Mars Scout mission outlined in this paper – effectively constitutes a set of independent reviews/assessments of the feasibility of the concept by academic institutions (Refs. 26-28). In all cases, these academic AHS design competition participants analytically verified the feasibility of the Mars rotorcraft concept. Further, funding from the NASA Institute of Advanced Concepts (NIAC) has been provided to university researchers (Ref. 29) for complementary work on a very small rotary-wing platform which has Mars exploration potential, among other applications. See Fig. 18a-c.



Fig. 19 – Mars Rotor Hover Test Stand

Table 3 – Proof-of-Concept Mars Rotor Description

Number of Blades	4
Rotor Diameter	2.438m
Blade Root Cut-Out (To simulate blade telescoping required for storage/transport)	40% blade span
Disk Loading (Nominal '1G')	4 N/m ²
Tip Mach Number	0.65
Blade Tip Reynolds Number	54,855
Thrust Coefficient, CT (Nominal '1G')	0.0108
Mean Blade Lift Coefficient	0.4
Blade Chord	0.3048m (constant) from 40% radial station outward
Rotor Solidity	0.191
Blade Linear Twist Rate	0 deg. out to 40% span; +2.4 to -2.4 deg. from 40 to 100% span.
Blade Weight	0.35 kg per blade
First Fundamental Elastic Modes	1.264 per rev – first flap mode; 1.118 per rev – first lag mode; 2.310 per rev – first torsion
Outer Blade Span Airfoil Section	Eppler 387
Spar Section	Circular tube with chordwise flat plate stiffener (30% chord)
Blade Construction	Airfoil fairing is milled foam with internal cavities; Circular graphite tube spar across complete span of blade; 45 deg. graphite chordwise flat plate stiffeners from 5% to 40% station; fiberglass leading edge cap on outer blade section airfoil fairing
Rotor Hub Configuration	Rigid/cantilevered hub, with tension/torsion straps, dry contact pitch bearings, and pitch arms at 5% radial station

A hover test stand, and a baseline proof-of-concept rotor (see Fig. 19 and Table 3), have been fabricated and are nearly ready for testing in a large environmental chamber – which can simulate Mars surface atmospheric conditions. This proof-of-concept rotor, though not as yet an optimized design, has been designed and fabricated to many of the exacting requirements dictated for a flight vehicle – including ultra-lightweight construction and blade dynamic tuning for low structural loads and vibration. The rotor airfoil used for this proof-of-concept rotor is the Eppler 387, a well-known low Reynolds airfoil. Recent unpublished two-dimensional airfoil test data in compressible, near transonic, test conditions at NASA Langley has been acquired for this airfoil, demonstrating moderately high lift coefficient values (R. Campbell - private communication). An advantage of rotorcraft, versus any other aerial vehicle proposed for Mars exploration, is the ability to conduct hover testing in existing ground-test facilities; additionally, it is also the unique advantage of the Mars rotorcraft concept that the most severe aerodynamic performance operating condition is in hover rather than forward-flight. Upon completion of

planned hover testing in a large environmental/vacuum chamber at NASA Ames, the Technology Readiness Level for the basic vehicle should increase to a TRL of 3, wherein test articles have been fabricated and performance assessed. The analytical tools used to date in assessing the aerial vehicle performance will be significantly upgraded in the near future by applying very sophisticated rotorcraft modeling tools to perform comprehensive analyses in forward-flight (Fig. 20) and Navier-Stokes CFD predictions of the Mars rotorcraft in hover. Confidence in these CFD predictions will be gained through validation against the experimental data resulting from the proposed proof-of-concept hover testing. Subsequent to the initial isolated rotor hover testing and the CFD work, a tethered 'flight' of a stripped down proof-of-concept vehicle in the Ames environment chamber will be pursued. This vehicle, by necessity because of Earth's higher gravity, will have to be powered by ground-based power sources and flight controllers (among other things) but will represent a major step ahead in the development of a Mars rotorcraft.

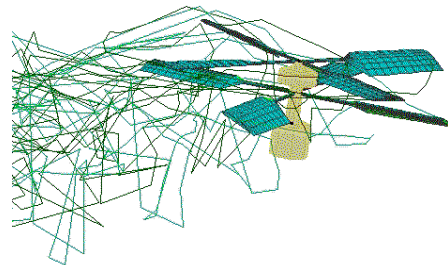


Fig.20 – Mars Rotorcraft: Putting Advanced Computational Analyses to the Test

The TRL for the autonomous system technology and flight navigation and control should be considered TRL=3, given past work performed within NASA and within various academic institutions (Refs. 32-33). A study, resulting from a university grant issued by NASA Ames to Carnegie Mellon University, has recently been completed examining from a conceptual design perspective the challenges and potential of using vision-based navigation systems for a Mars rotorcraft; these preliminary results were very encouraging. A complementary research program within NASA Ames, funded by the Automated Reasoning element of the NASA Intelligent Systems program, is currently underway and is likely to significantly aid in the development of a flight controller/mission computer and software for a Mars rotorcraft -- as well as other, terrestrial applications.

The propulsion technology (electric motors and fuel cells (primary option) or hydrazine -- aka Akkerman reciprocating engines – (as secondary, back-up option) should be considered to be TRL=3 for past work performed by NASA, Industry, and academic institutions. Some very exciting innovative

propulsion system concepts were developed as a result of the AHS student design competition.

Proposing the use of a rotary-wing aerial platform for a Mars Scout mission is not as mature a technical approach as many other concepts likely to be advocated for Mars Scout missions. And yet, the Mars rotorcraft concept offers such a tremendous potential increase in mobility for Mars exploration, with a corresponding near-order-of-magnitude increase in mission productivity, that a modest investment now, for the future, should be justifiable.

Martian aerial scouts offer the potential to dramatically expand the surface area of Mars that can be explored in future missions. By flying over difficult topography, aerial vehicles are capable of covering much more area than a rover in significantly less time. The 2003 mission Mars Exploration Rovers will cover approximately 100 meters per Sol; a Mars rotorcraft could cover over twenty times that distance per flight (assuming a seven day between-flight cycle for vehicle recharging and data analysis/transmittal to Earth). By operating above the ground surface, the potential line of sight of sensor systems also greatly expands. A Martian aerial scout flying at 100m AGL would have a line of sight in excess of 25 km compared to the 5 km line of sight of a ground based vehicle assuming flat terrain.

Powered-flight aerial vehicles are superior to balloons/aerostats in all respects, except maybe, simplicity. However, even with respect to their conceptual simplicity, one has to acknowledge that balloons, as represented by their terrestrial counterparts, are not without their own unique failure mechanisms (for example, the early attempts to fly the erstwhile Ultra Long Duration Balloon experiments). The ability to select an area of interest on the Martian surface, direct a powered aerial vehicle to that location, and to survey and conduct experiments as desired is essential for superior scientific investigations of Mars. Having a balloon passively, uncontrollably, skirt across the planet will be of modest benefit at best.

Vertical lift aerial vehicles – including rotorcraft -- combine the exploration area advantage described above with the ability to takeoff and land in unprepared sites of scientific interest. Unlike “single shot” fixed wing aircraft concepts, a vertical lift aerial scout offers the opportunity to perform multiple mission sorties by recharging at the lander site. A vertical lift aerial vehicle solution enables sample return missions. Samples could be gathered from a wide radius to a lander/primary-base. As demonstrated on Earth, rotorcraft uniquely have superior low-speed handling qualities. Rotorcraft Mars scouts would enable low-speed, precise movement in three dimensions allowing the craft to closely study cliff walls or capture a 360° surface

view of large objects. Highly sloped terrain, possibly resultant from erosion, can be thoroughly studied. This terrain will remain unexplored by ground vehicles or fixed wing aircraft concepts while a rotorcraft can fly low to the ground, allowing great image detail. Low speed handling qualities make takeoff and landing operations possible in unprepared terrain. Finally, fixed-wing aerial vehicles suffer from substantial technical challenges in their release from entry vehicles in descent, or launch/catapulting from ground-based assets. Even hypersonic rocket-propelled ‘fixed-wing’ aerial vehicles -- that are both entry vehicle as well as aerial scout -- pose significant technical challenges; such hypersonic aerial vehicles have very limited developmental heritage for terrestrial applications, let alone their readiness for planetary exploration missions.